

TRANSITION EDGE SENSORS

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Materials Science Division

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Detector Development Seminar @ High Energy Physics Division / ANL

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Outline

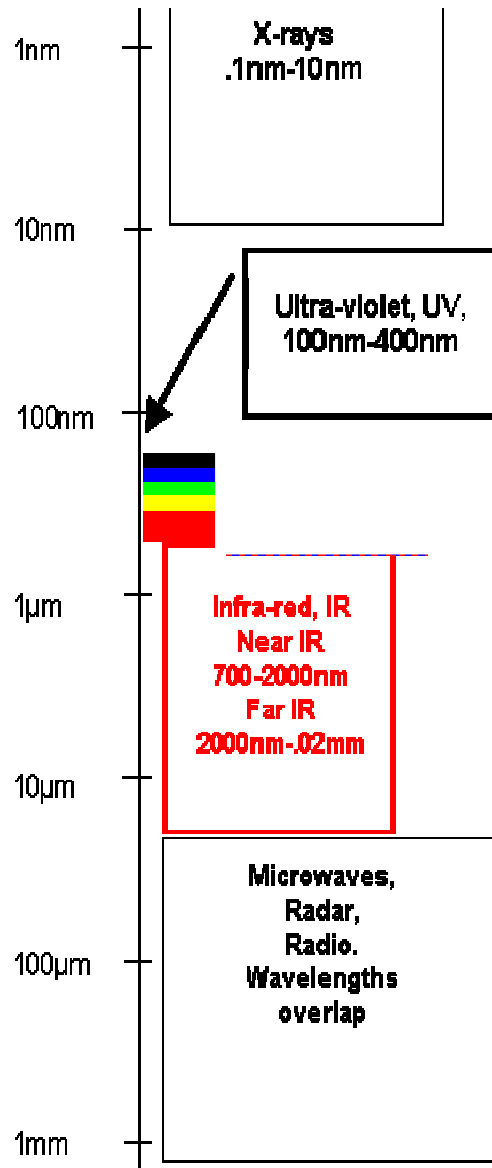
Introduction: Superconducting Transition Edge Sensors (TES)

- 1. Thermally activated superconducting microbolometer -new approach for broadband imaging (past research)***
- 2. Low temperature TES for microwave astronomy (current efforts)***
 - 2.1 Polarization sensitive TES***
 - 2.2 Multicolor TES array***

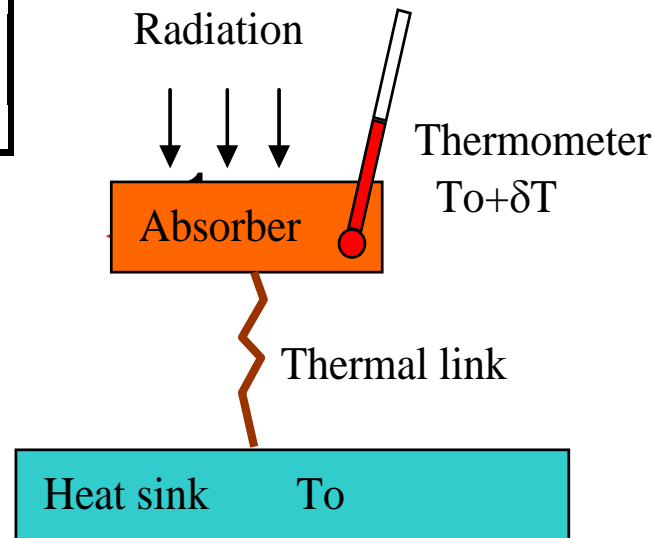
Summary

Transition Edge Sensors (TES) - thermal detector

BASED on CONVERSION : EM Radiation \longrightarrow Temperature Change \longrightarrow Electrical signal

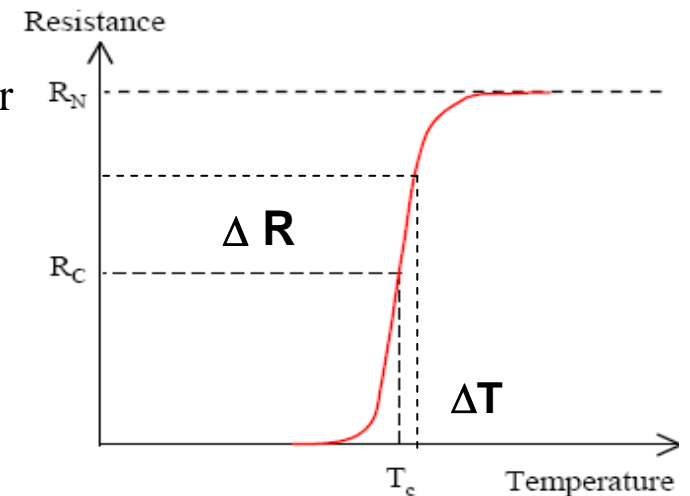


Common scheme



COMPONENTS:

Absorber, Thermometer, Thermal link;



SC transition

Spectral range is defined by absorber

MOTIVATION: Development of advanced technologies for broad band imaging

An application example – γ -rays detector

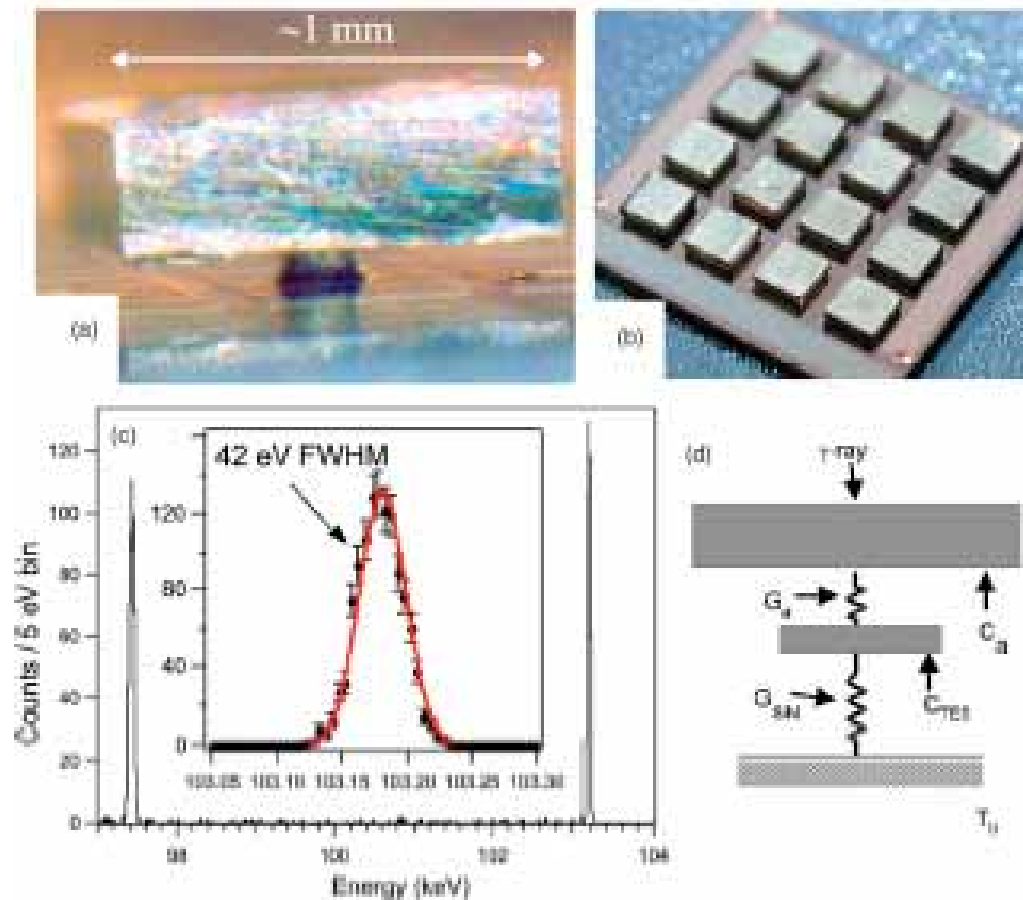
APPLIED PHYSICS LETTERS 89, 124101 (2006)

Array-compatible transition-edge sensor microcalorimeter γ -ray detector with 42 eV energy resolution at 103 keV

B. L. Zink, J. N. Ullom, J. A. Beall, K. D. Irwin, W. B. Doriese, W. D. Duncan, L. Ferreira, G. C. Hilton, R. D. Horansky, C. D. Reintsema, and L. R. Vale^{a)}

National Institute of Standards and Technology, 325 Broadway MC 817.03, Boulder, Colorado 80305

(Received 11 March 2006; accepted 21 July 2006; published online 20 September 2006)



TES improvement

Main parameters:

Responsivity (S_λ) = (output signal)/(input power) $(S_\lambda) \sim \epsilon_\lambda (1/G) (dR/dT)$

Noise Equivalent Power (NEP) = (Electrical noise)/(responsivity)

ϵ – absorption coeff., G -thermal conductance (W/K)

$$\text{NEP}^2 (\text{ideal detector}) \sim 4kTR/S^2 + 4kT^2G$$

1.Single pixel detector optimization: $(T) \downarrow$ $(dR/dT) \uparrow$ $(G) \downarrow$ $(\epsilon) \uparrow$

Not only materials but design determines main parameters

2.Increasing the number of detectors in array



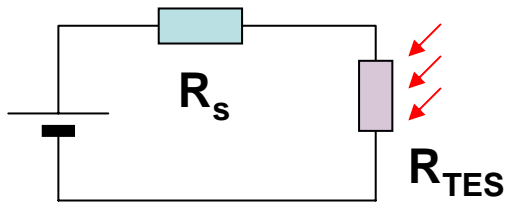
Microfabrication (*uniformity and reproducibility*)

Some problems of large TES array

1. Stability

Sharp transition (dR/dT) leads to a greater tendency for instability and lower saturation energy.

Electro thermal feedback for stability



$$\Delta R \rightarrow (\Delta U; \Delta I) \rightarrow \Delta P_J$$

$$1) R_s \gg R_{tes} \quad I \sim \text{const} \quad \Delta R \uparrow \quad \Delta U \quad (+\Delta P_J) \uparrow$$

$$2) R_s \ll R_{tes} \quad U \sim \text{const} \quad \Delta R \uparrow \quad (-\Delta I) \quad (-\Delta P_J) \downarrow$$

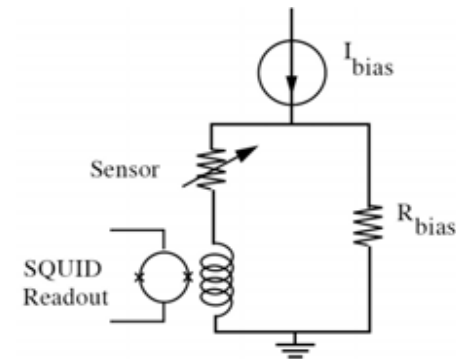
negative feedback means that the detector is self-biasing.

2. Read-out from large array

Cryogenic multiplexed readout electronics is needed. Traditional semiconductor read-out schemes are not suitable for low temperature.

For low temperature TES - SQUID electronics

Low noise $\sim 2\text{pA}/\text{Hz}^{1/2}$, low impedance



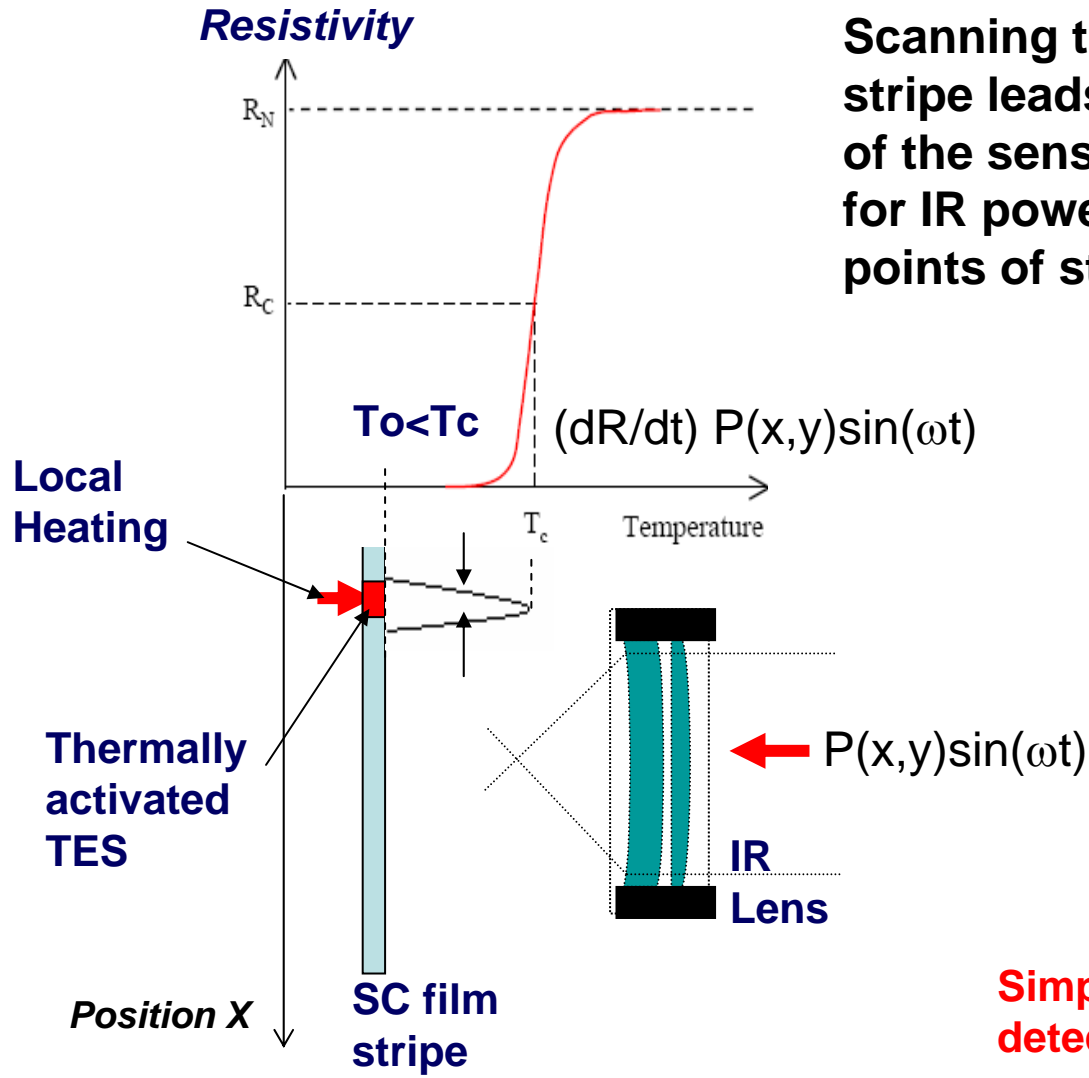
NIST

Berkeley Lab

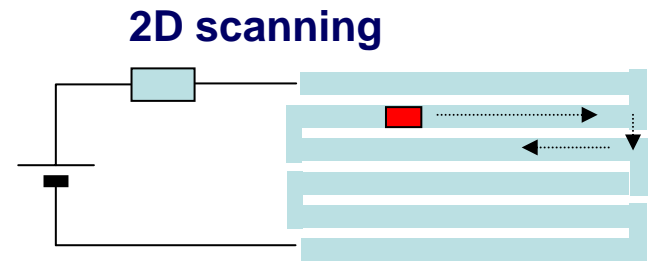
Caltech

Hybrid
design

1. Thermally activated TES - new approach for read-out .



Scanning the local heating along the stripe leads to physical displacement of the sensitive area and, may be used for IR power measurement in each points of stripe (basis for imaging).



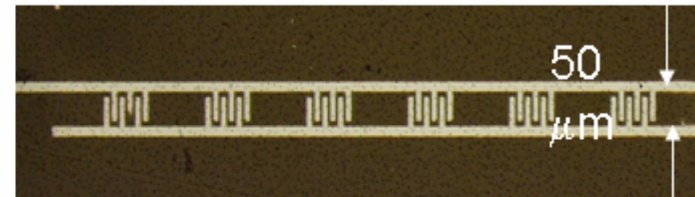
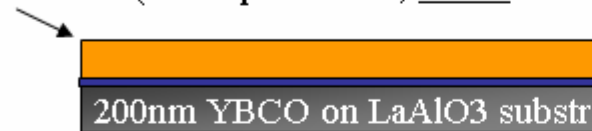
Simple structure - equivalent to 2D detector array, broadband

HTSC devices - Microfabrication process

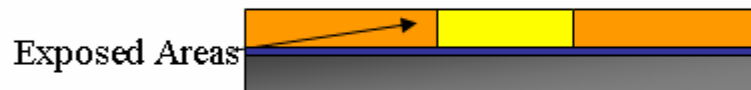
E-beam lithography (Raith-150 at CNM) , wet etching

E-beam Resist Spin-coating

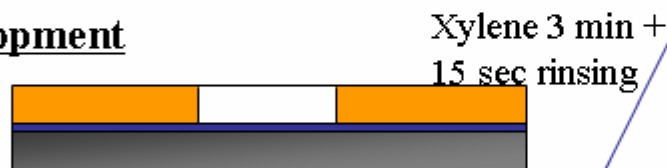
ZEP 520A Resist (2000 rpm / 1 min; 180 C / 2 min)



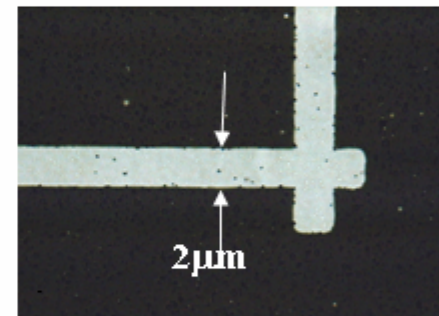
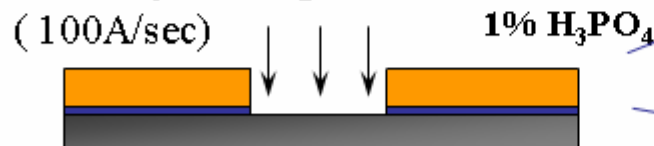
EB Patterning (100 pA)



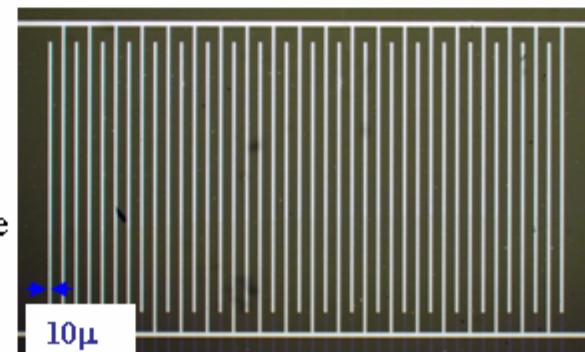
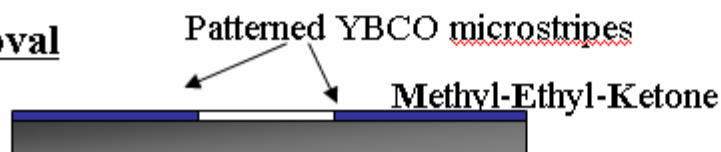
Resist Development



Wet chemistry etching

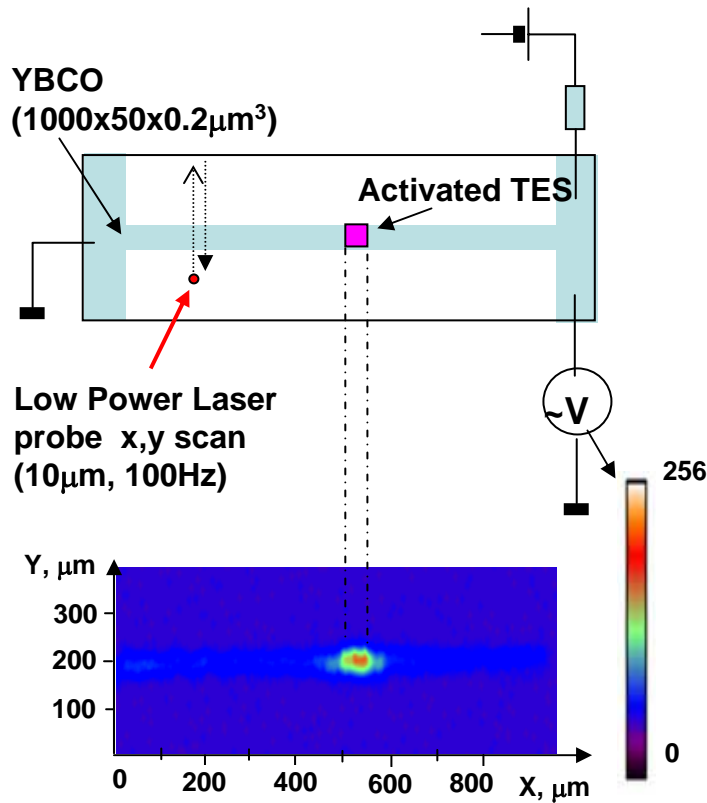


Resist Removal

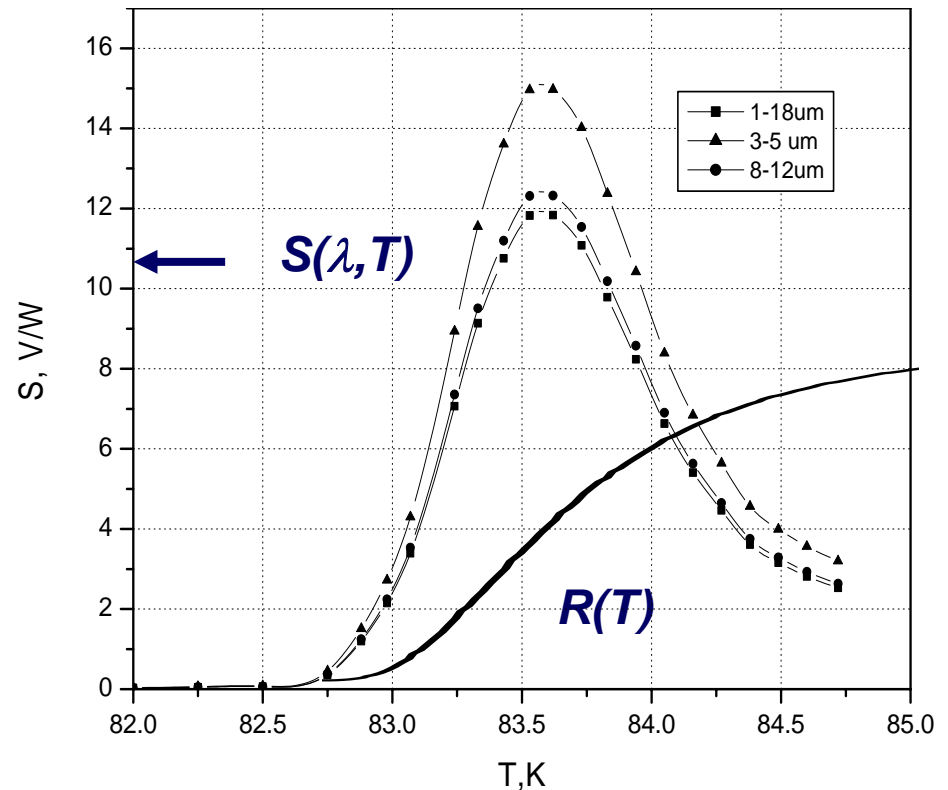


Characterization of Thermally activated TES

Spatial distribution of photo-response $S(x,y)$



Temperature dependence of the photo-response for spectral ranges 1 - 18, 3 - 5, 8 - 12 μm .

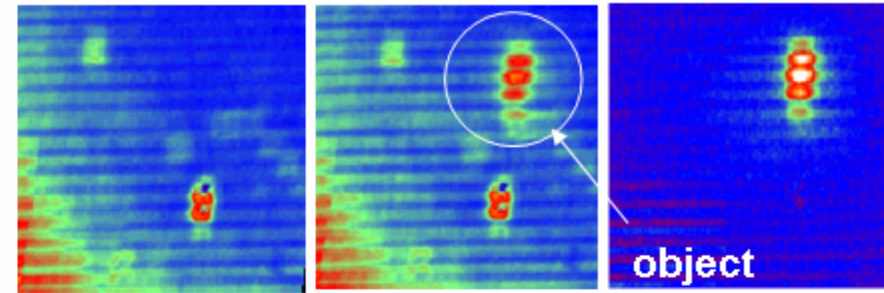
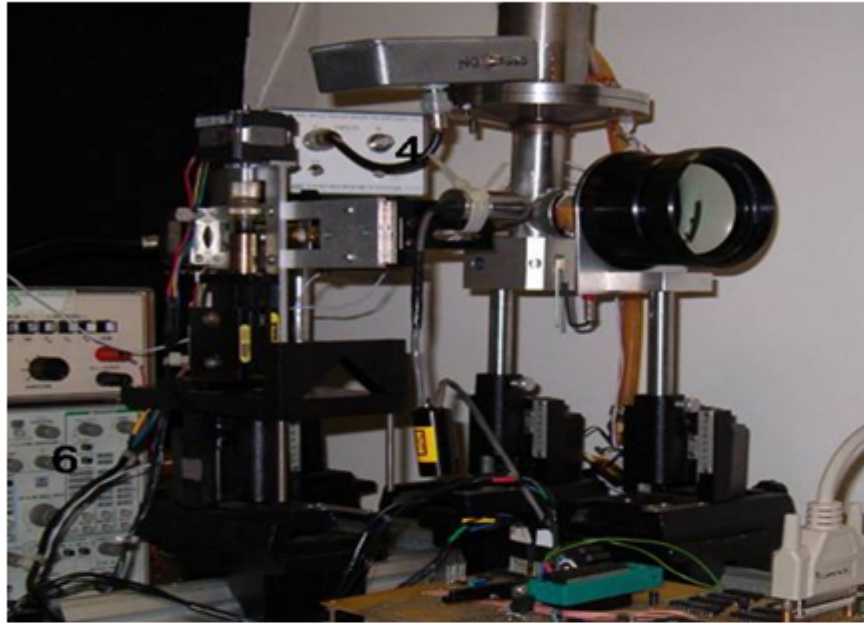


Activated TES size \longrightarrow **$\sim 100 \times 50 \mu\text{m}^2$** Diffraction limit for IR $\sim 50 \mu\text{m}$

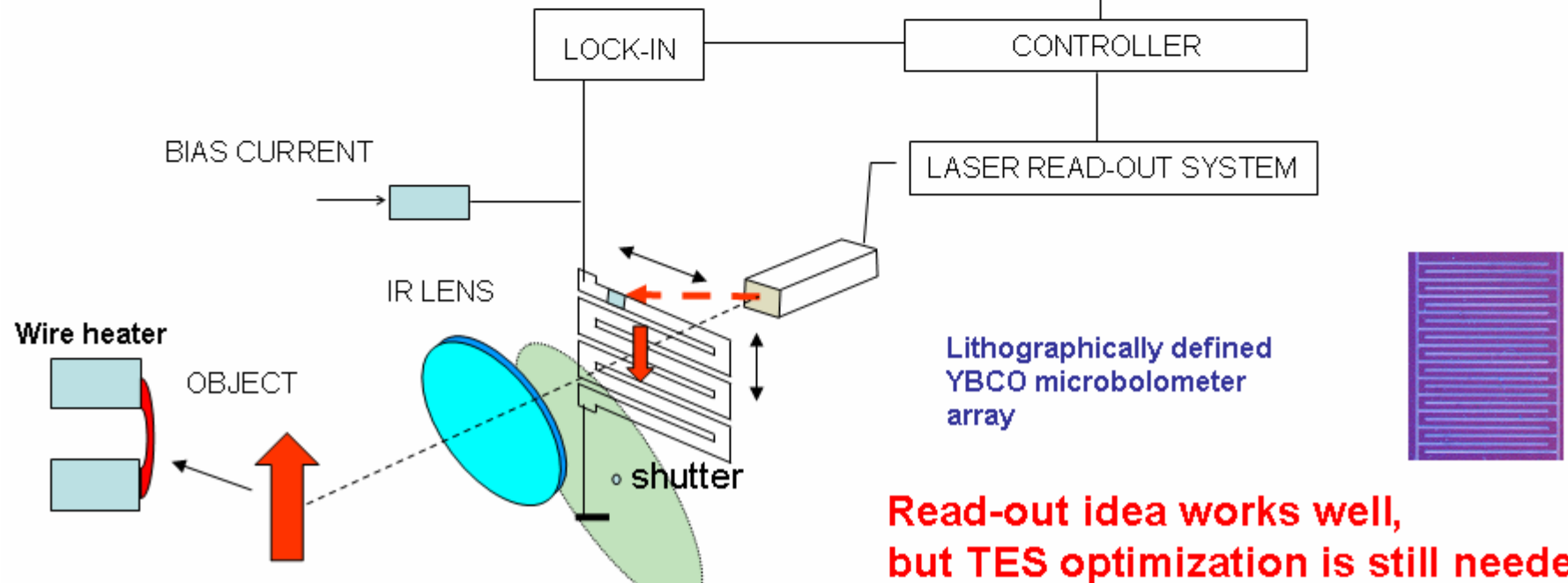
NEP \rightarrow **$\sim 10^{-10} \text{W/Hz}^{1/2}$** Power, temperature resolution

Time constant \longrightarrow **$\tau \sim 10^{-3} \text{sec}$** Frame time

Imaging set-up based on thermally - activated TES



- a) background signal (32x32 "effective" pixels array)
b) detected "hot" spot ("as is")
c) after background subtraction



**Read-out idea works well,
but TES optimization is still needed !**

2. *Low temperature TES array for astrophysics*

- Through this **partnership project between Argonne National Laboratory and University of Chicago**, we aim to develop *state-of-art* superconducting Transition Edge Sensor technology for astrophysics applications. These sensors are required for the next generation of Cosmic Microwave Background (CMB) polarization measurements, the goal of which is to probe the beginnings of the universe by detecting or setting an upper limit on the energy scale of Cosmic Inflation.

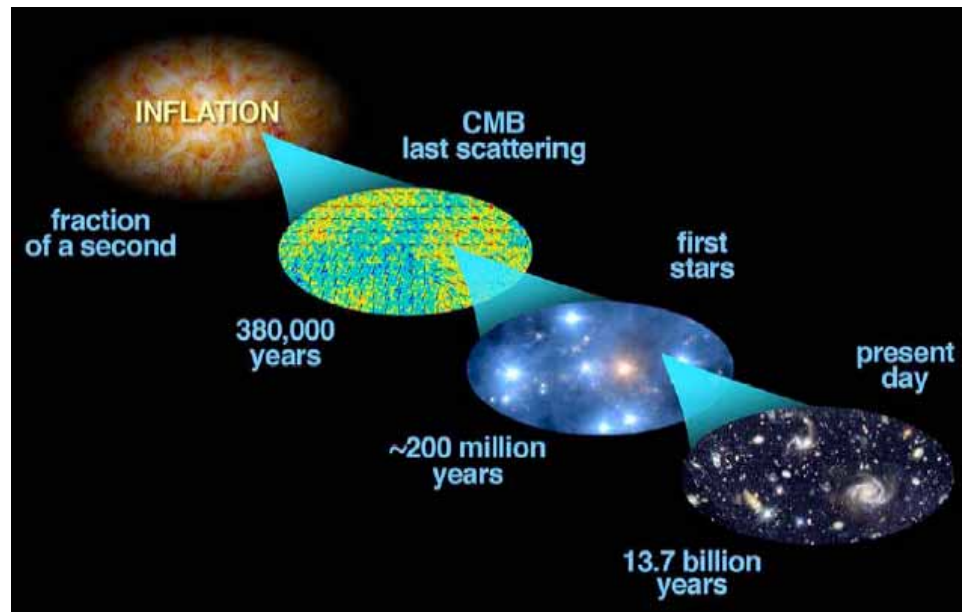


Figure: Stages in the evolution of the Universe. According to the cosmological standard model, inflation stretches microscopic quantum fluctuations into astronomical density fluctuations that leave an imprint on the cosmic microwave background (CMB), and then grow into the present day galaxy distribution (picture taken from NSF2006 Task Force Report on CMB).

2.1 - Polarization-sensitive TES

- for use in sub-millimeter and millimeter-wave astrophysics projects, in particular for measuring the polarization anisotropy of the CMB with the 10-meter South Pole Telescope (SPT) being built by the University of Chicago and collaborators.



*The South Pole Telescope
deployed at the South Pole.*



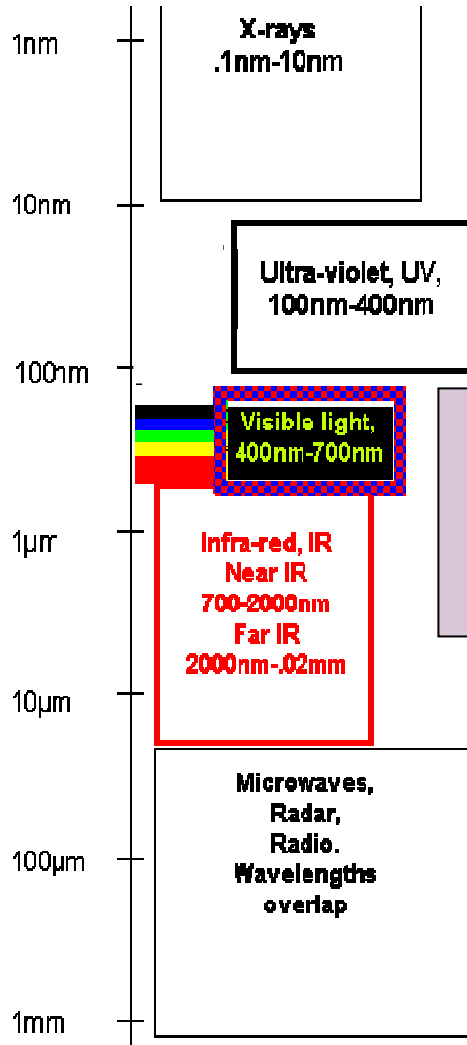
*South Pole Telescope science
team leader John Carlstrom (UC).*

Low temperature TES array for microwave astronomy

Potential observations bands * for the SPT instrument

λ , μm	ν , GHz	$\Delta\nu$, GHz	G, W/K
870	345	27	4×10^{-10}
3150	95	24	2×10^{-10}

For background limited performance



$S_{\lambda} \sim \epsilon_{\lambda} (1/G) (dR/dT)$ (polarization, microwave)
 $NEP^2 (\text{detector}) = 4kTR/S^2 + 4kT^2G < NEP^2 (\text{background})$
 $T_o > 0.3\text{K}$ (cooling system limit)

$(T) \downarrow$ $(dR/dT) \uparrow$ $(G) \downarrow$ $(\epsilon) \uparrow$

First stage task (in progress):

Electronic and thermal properties control and optimization (T_c , dR/dT , G)

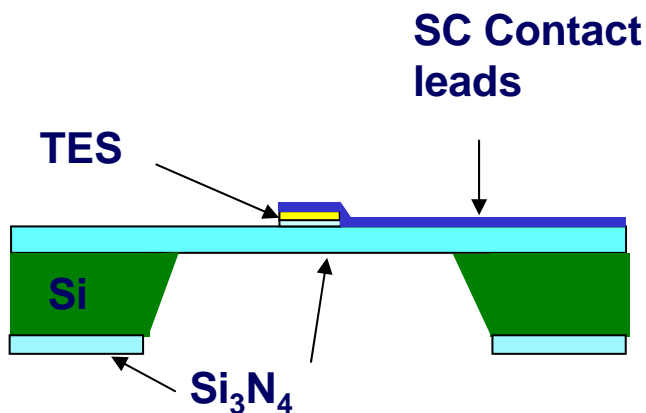
*J. E. Ruhl, P. A. R. Ade, J. E. Carlstrom, H. M. Cho, T. Crawford, M. Dobbs, S. S. Meyer et al. "The South Pole Telescope", Proc. SPIE, Vol. 5498, p 11-29, 2004

Simplified flow diagram of the fabrication process for a TES.

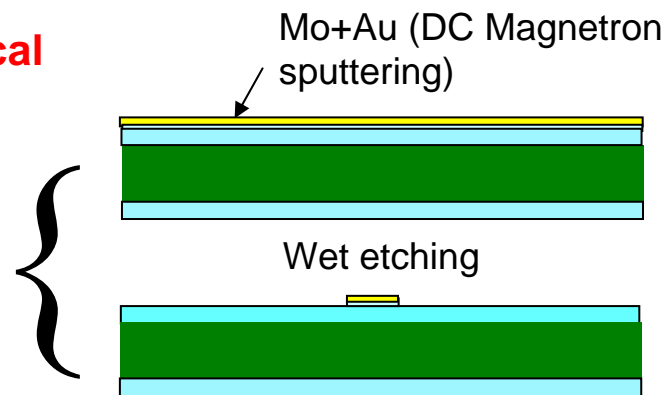
Multilevel optical lithography

For thermal conductance $< 100 \text{ nW/K}$

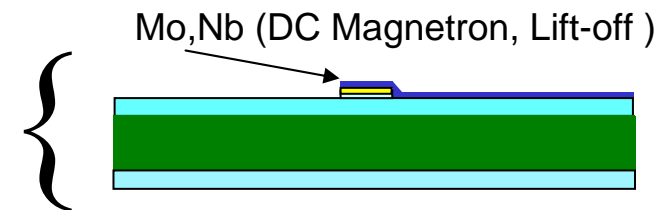
Membrane design



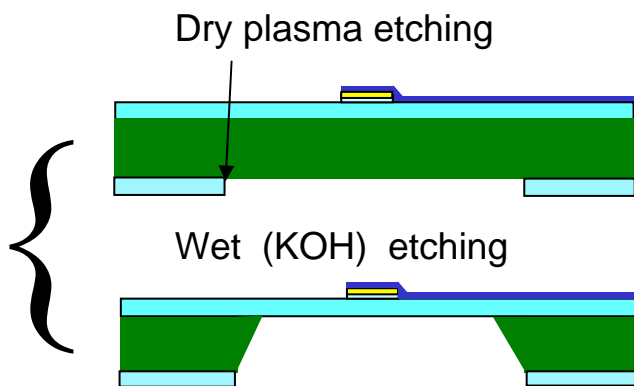
**1. TES fabrication:
film deposition,
patterning, wet
etching**



**2. SC leads
fabrication:
deposit. ,
patterning, lift-off**



**3. Membrane
fabrication:
pattern., RIE, KOH
wet etching**

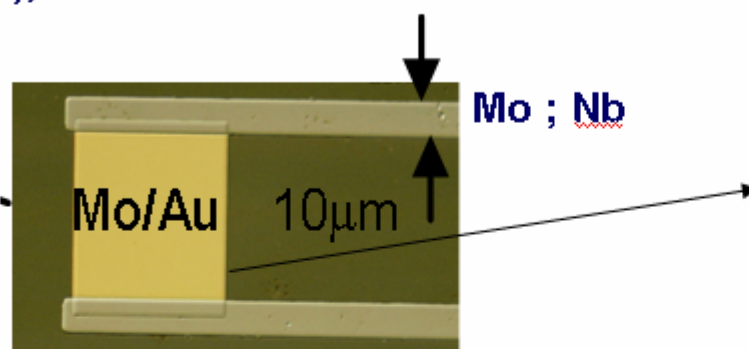


mask design, materials choice, etching processes optimization

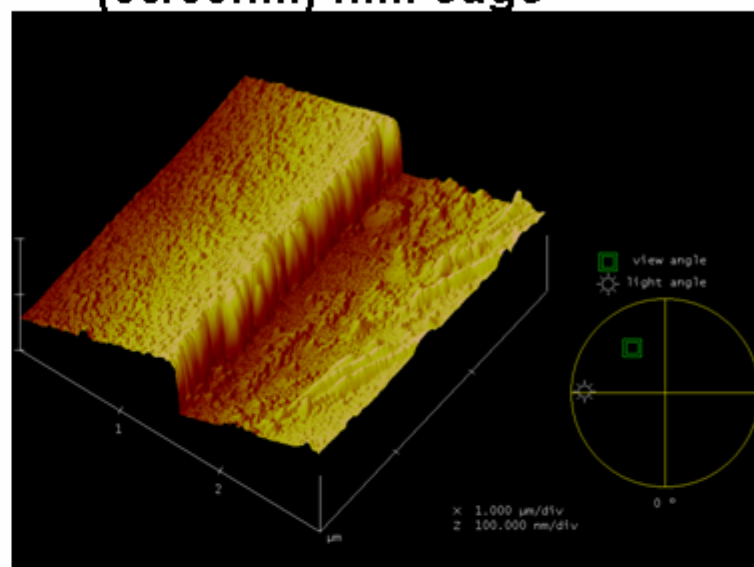
Critical Temperature optimization

Operation $T \sim 0.5\text{-}0.6\text{K}$ Proximity effect

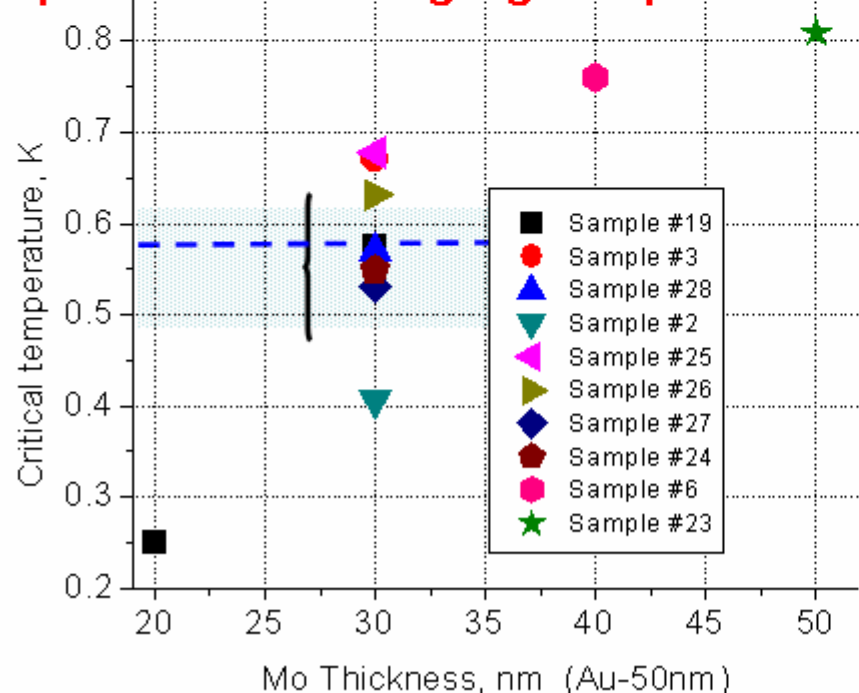
Mo ($T_c = 1.1\text{K}$), Au-normal metal



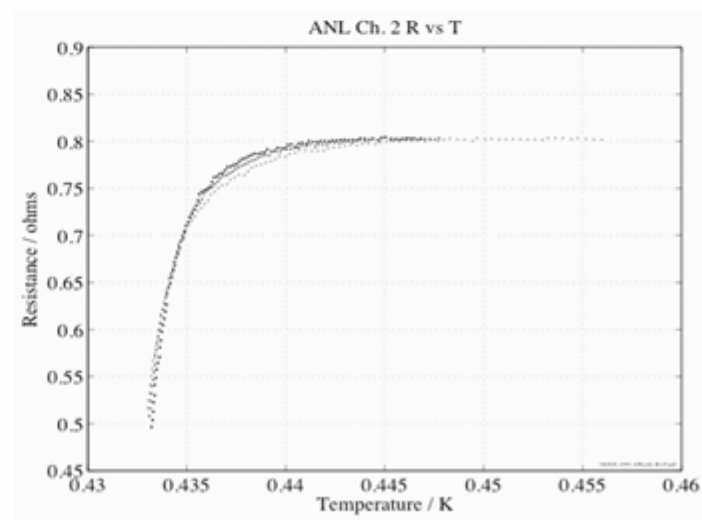
AFM picture of Mo/Au
(30/50nm) film edge



Deposition and etching regime optimization



$\Delta T = 5\text{-}10\text{mK}$ $dR/dT = 100\text{-}200\Omega/\text{K}$

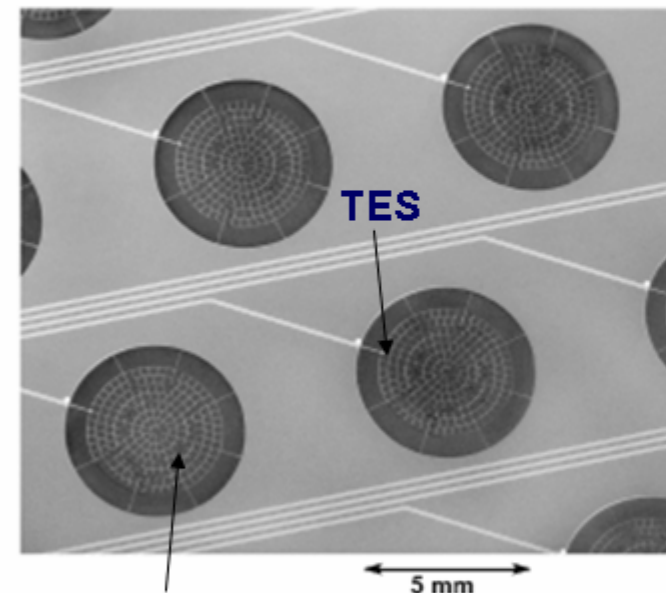


Thermal link Optimization

For SPT application 200-400pW/K

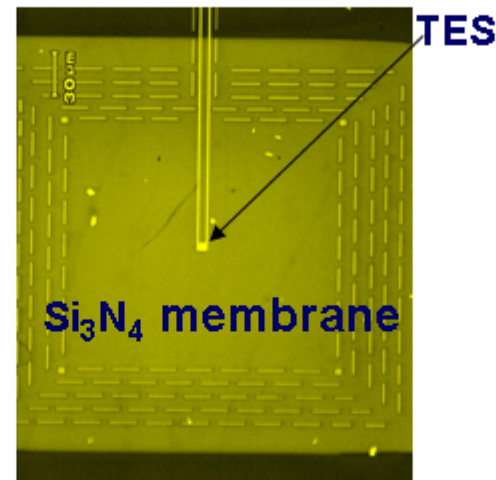
Si_3N_4 membrane ($3000 \times 3000 \times 1.5 \mu\text{m}^3$) – 3nW/K

Spider web design < 100pW/K
(Berkeley Lab)

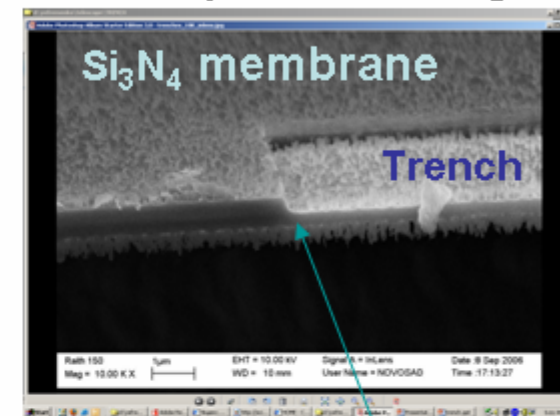


Si_3N_4 “spider web”

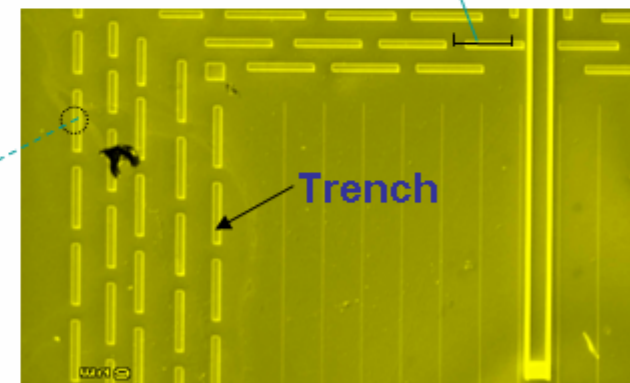
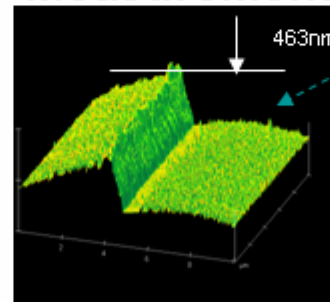
Metal leads for optimization



Trench profile SEM image



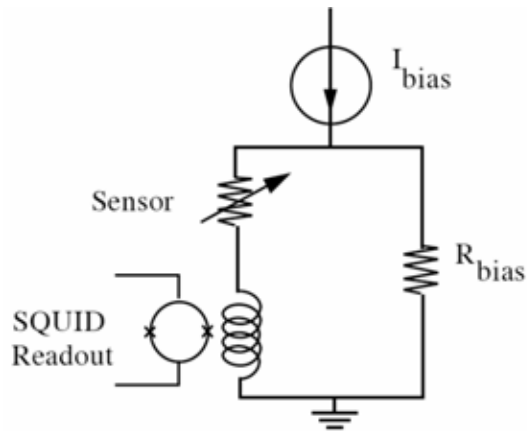
AFM depth measurement



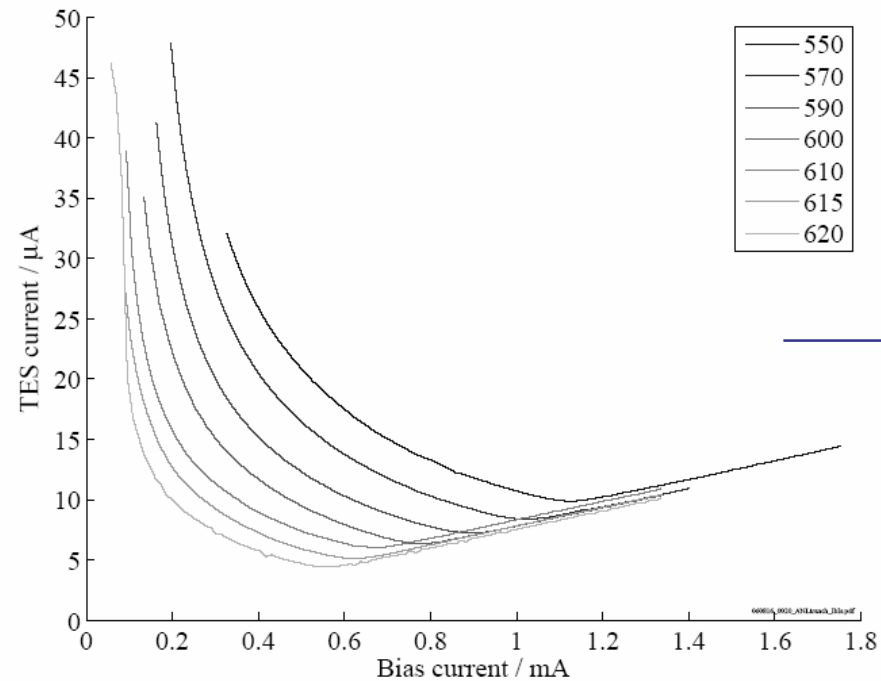
$G = \sim 700 \text{pW/K}$ at 0.6K Trenches ~450nm depth

Surface scattering determines thermal transport

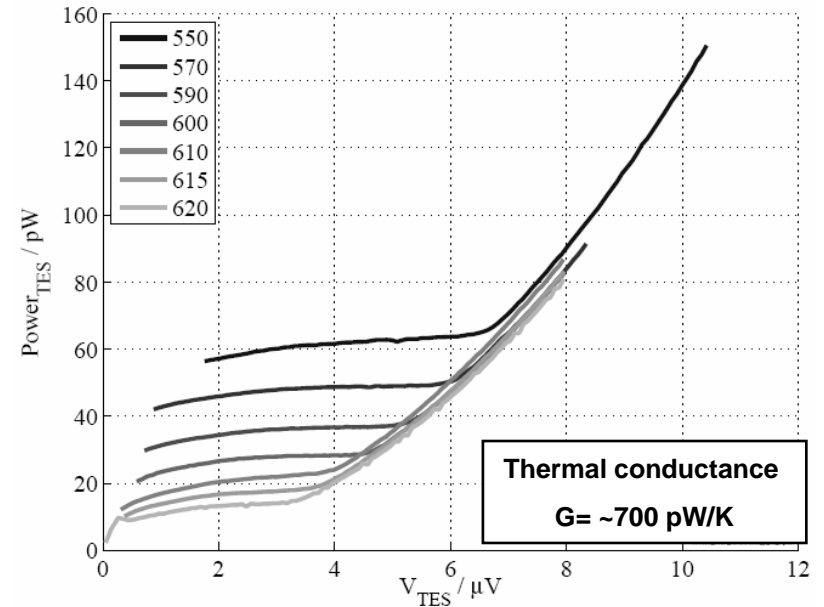
Optimized thermal conductance



ANL trenches

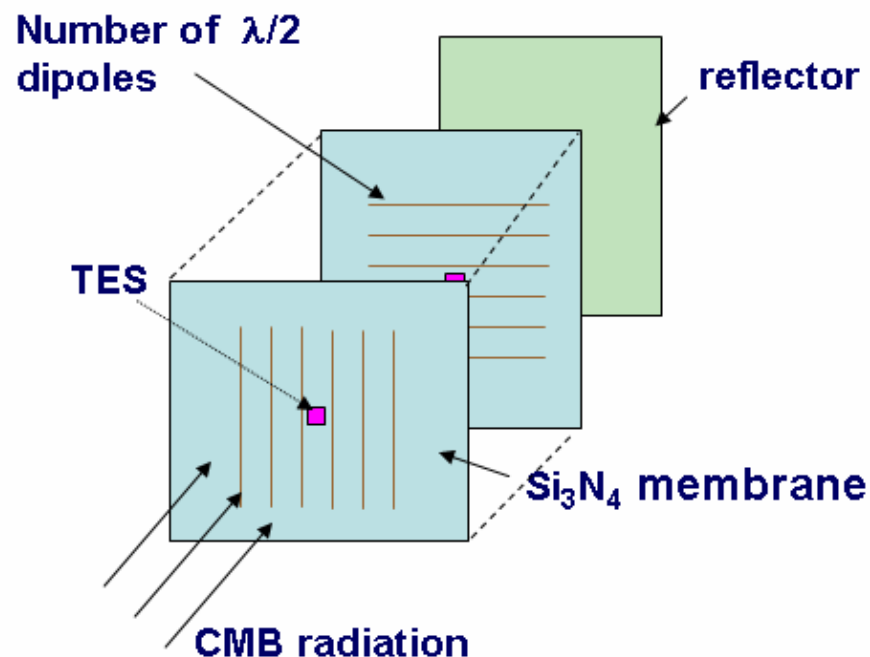


ANL trenches power vs voltage



Absorber optimization

Goal - polarization sensitive detector array



Resistance matched to the impedance of free space $Z \sim 377 \Omega/\text{sq}$

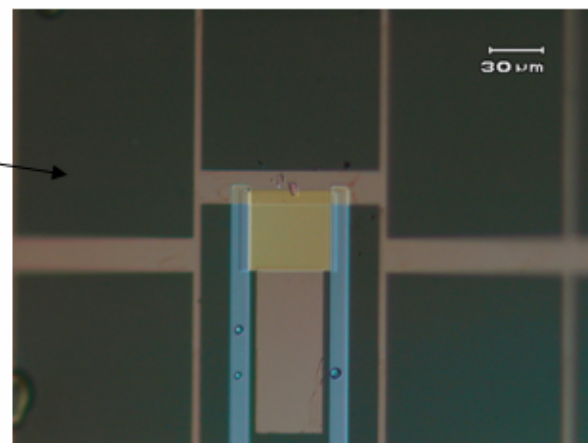
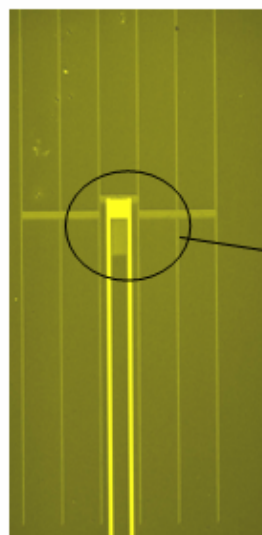
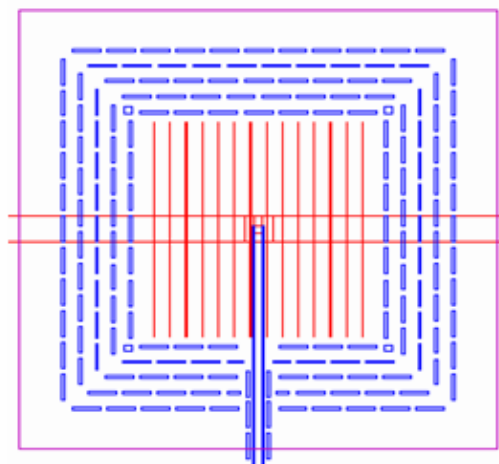
Simulation for 95GHz
14 stripes, length 1.660mm,
width $3 \mu\text{m}$, $R = 7 \Omega/\text{sq}$

Au, thickness 11nm

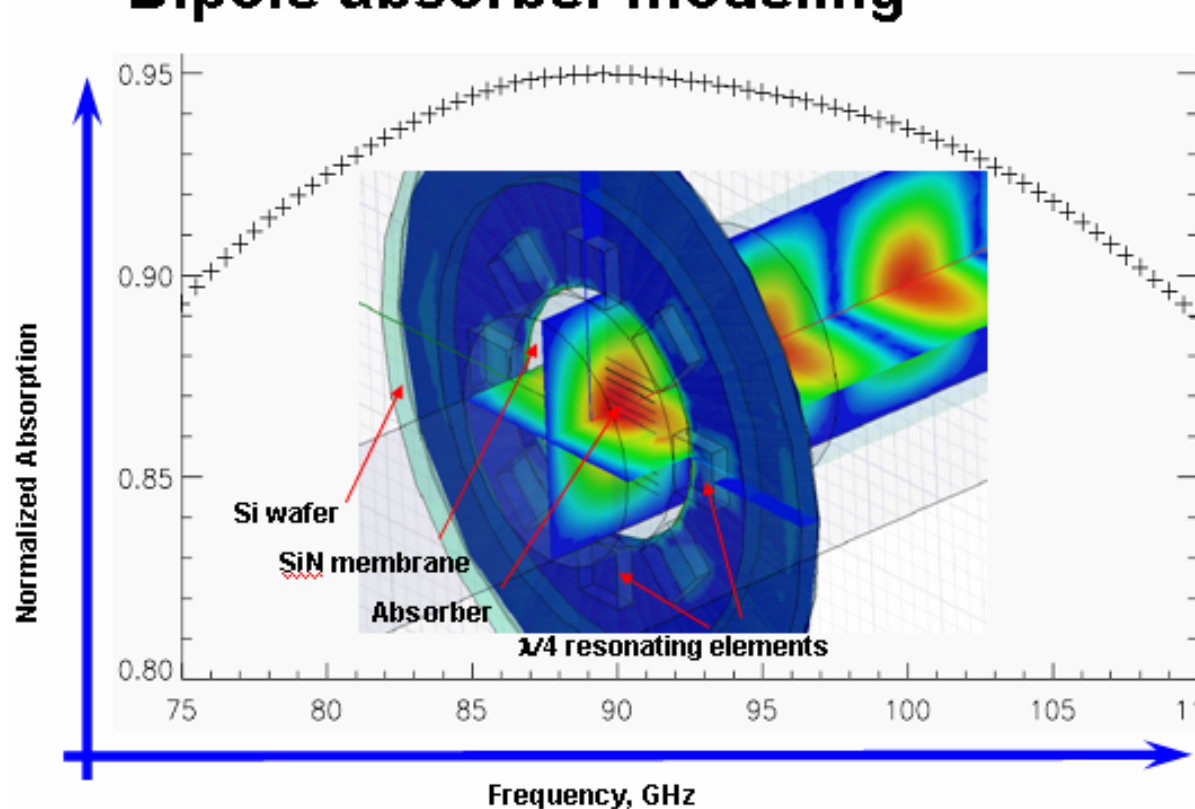
$$\text{NEP} \sim 1/\epsilon$$

$$S \sim \epsilon$$

Mask design of absorber coupled TES



Dipole absorber modeling



Target frequency - 95GHz,
absorption efficiency – 95 %
14 stripes, 1.6 mm long, 3μm wide,
11 nm thick, sheet resistance - 7Ω / □

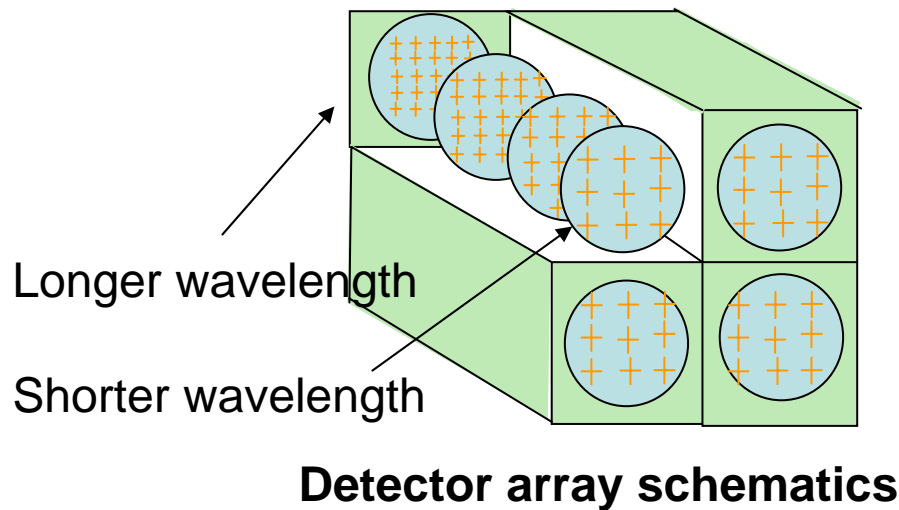
Polarization sensitive TES - next steps

- testing absorber efficiency
- microfabrication of prototype device pair with optimized TES / absorber
- dark and optical low temp measurements
- Noise characterization
- Implementing SQUID-based read-out for a single-pixel pairs and detector array
- Fabrication of large format array (~1M pixels) for polarization-sensitive measurements for the South Pole Telescope observation

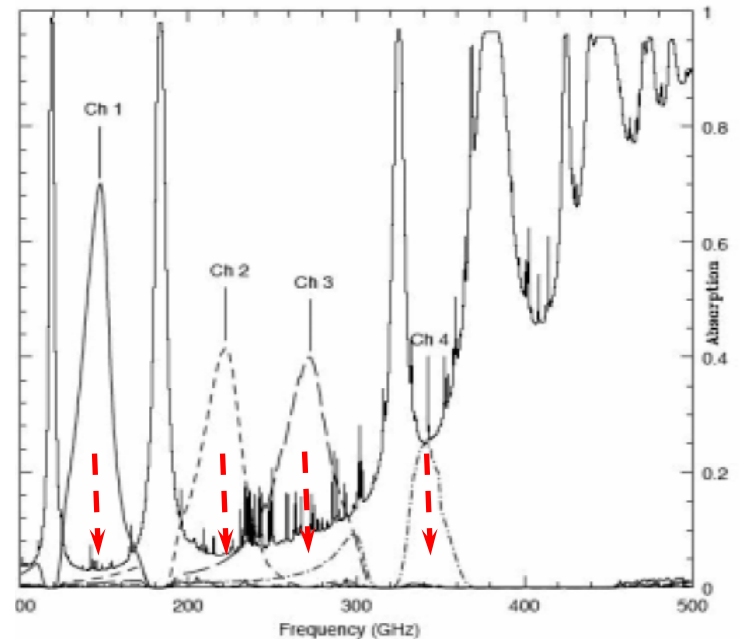
2 - Multicolor TES array

- Part of SPEctral Energy Distribution (SPEED) project* to study the spectral energy distribution of high redshift galaxies;
- 4 x 4 pixel array operating @ sub 0.5 K temperatures;
- each pixel is a frequency selective bolometer stack that enables sensing radiation at 150, 220, 270, 350GHz.

- **Simultaneous spatial and spectral measurements**

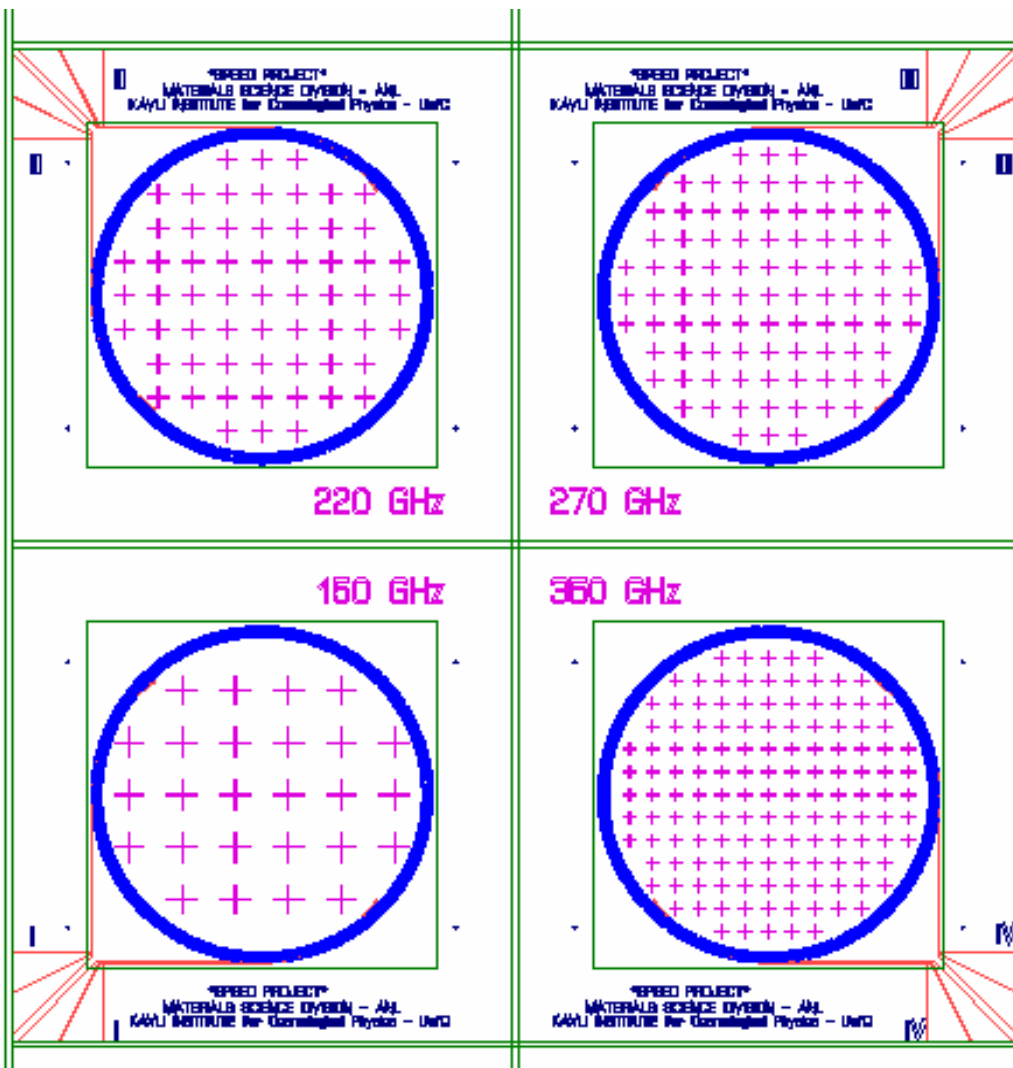


frequencies of interest were chosen to
↓ account for atmosphere absorption spectra

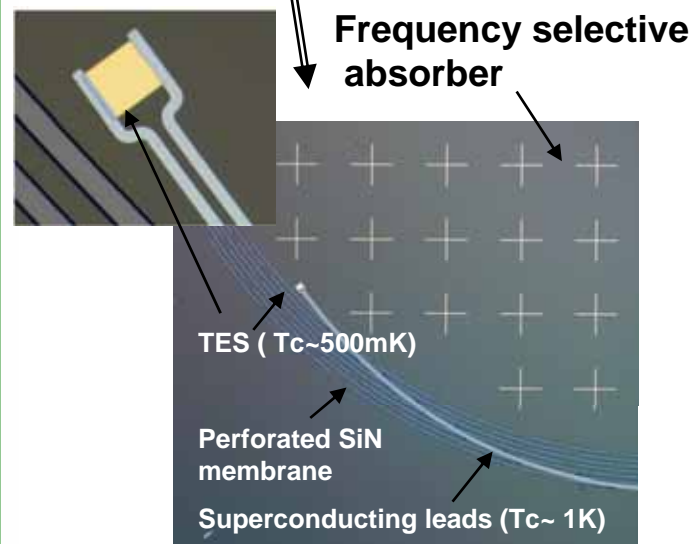
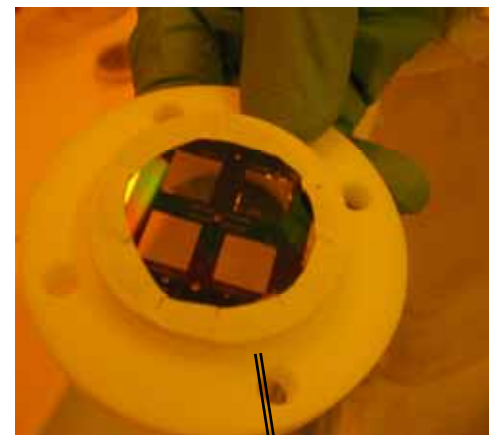


(*) SPEED collaborators: Enrico Fermi Inst. UofC, NASA/Goddard Space Flight Center, Univ. of Wisconsin, Univ. Of Massachusetts, and others

Absorber mask layout

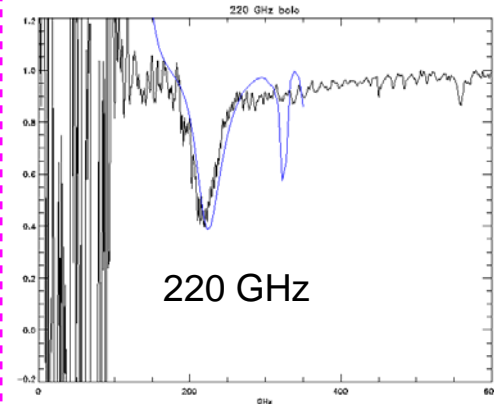
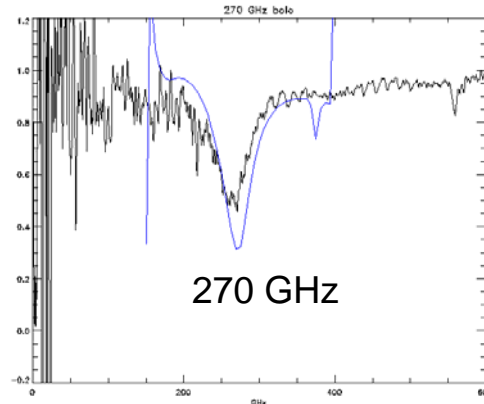
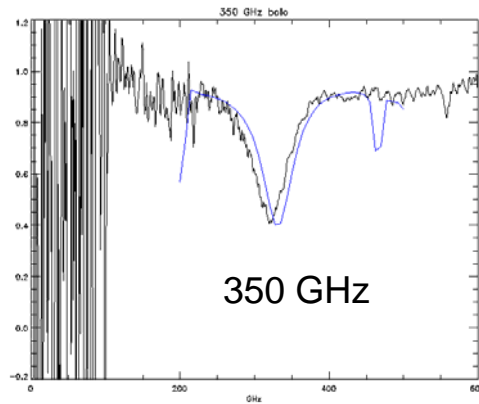


Prototype

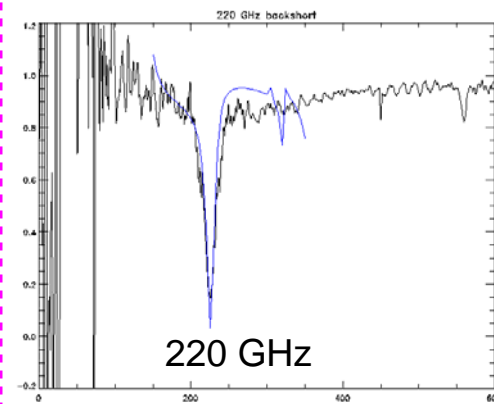
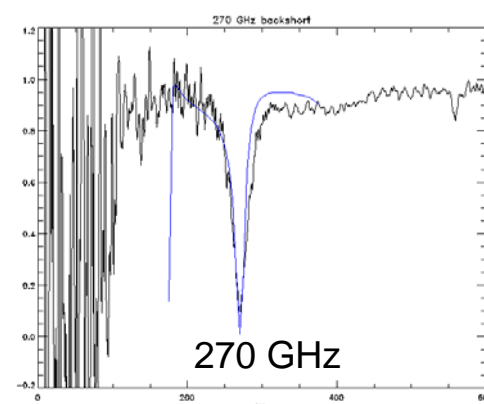
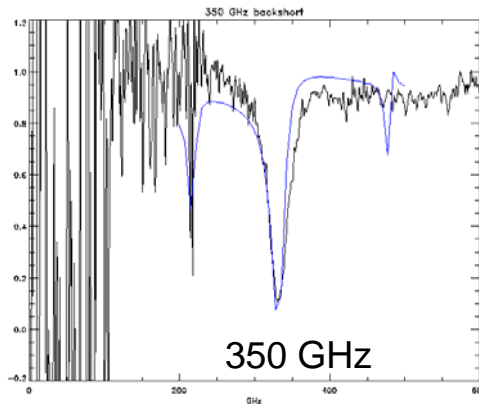


Transmission measurements (May 9, 2007 *)

Absorbers



**Backshort
reflector**



* Courtesy of Dr Thushara Perera, University of Massachusetts

Multicolor TES array- next steps

- testing absorber / reflector combined efficiency
- micro fabrication of prototype array (4 x 4 pixels)
- dark and optical low temp measurements
- Noise characterization
- Implementing SQUID-based read-out for a single pixel pairs and detector array
- Device assembling for ground telescope observation

Future..

The goal is to improve TES characteristics and to establish state-of-the-art bolometer *science & technology* at Argonne. Existing instrumental capabilities include high quality metallic films synthesis (MSD), multilevel lithography (CNM), advanced characterization (MSD and CNM) and sub-Kelvin temperature measurements (UofC and MSD).

Enabling the detector technologies necessary to move beyond current measurement limitations.

Future bolometric detector arrays will be the mainstay of Astrophysical and Cosmological experimental efforts at mm and sub-mm wavelengths using ground-, balloon- and space-based platforms.

The same type of detector technology (but with different radiation absorber) can also be applied to soft and hard x-ray detectors (demonstrated energy resolution of 4.5 eV at 6 keV). Such detector technology could be adapted for use in x-ray imaging for synchrotron radiation research at the APS. Moreover, highly-sensitive broadband detector systems are among crucial components in DHS / DoD programs (THz, gamma-rays imaging devices etc).